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LIGHT-FRAME WALL SYSTEMS: PERFORMANCE AND  
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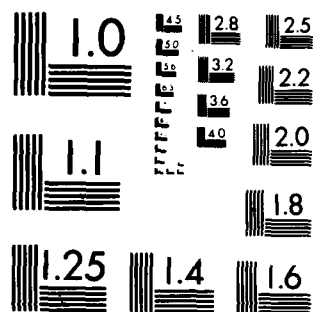
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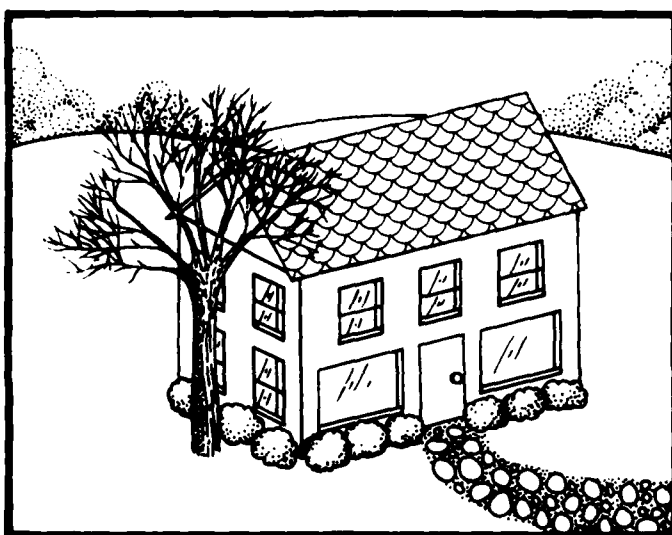
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## Abstract

Conventional analysis methods seriously underestimate the strength and stiffness of light-frame wall systems. To better predict the strength and stiffness of these systems, a finite element based computer program, FINWALL, has been developed at Oregon State University (OSU). Previous testing at OSU during model development can now be augmented by the tests described in this paper to provide additional model verification.

Test results are presented for 10 walls loaded under a constant axial and uniform increasing lateral load to failure. Failure loads ranged from 88 to 130 pounds per square foot (lb/ft<sup>2</sup>) of lateral load, corresponding to about 4 to 6 times design load. Average stud deflections at a common design load of 20 lb/ft<sup>2</sup> were 0.09 to 0.21 inch (span/deflection ratio average = 600).

Predicted performance, based on the computer model, is compared with test results. Average strength and deflection are predicted at 1.10 and 1.06 times test values, respectively. Model sensitivity to stud failure deflections and problems with load application during some of the tests added considerable variability to the model predictions. Potential applications of the model to codes and standards are discussed.

## Acknowledgments

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Paper  
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# Light-Frame Wall Systems: Performance and Predictability

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## Introduction

Light-frame wood structures have performed well over the years. However, accurate prediction of their performance by analytical means was not feasible until the development of computer-based analysis techniques. The objectives of this study were to experimentally measure the strength and stiffness of a typical wall configuration and to compare test data with analytical predictions of performance.

This study is part of the light-frame construction research program (Hans et al. 1977) initiated at the Forest Products Laboratory to address performance in a broad context. Structural performance is only one facet of this program, and walls represent but one of the structural components in a building. The overall program objectives and accomplishments in other areas are reported elsewhere (Forest Products Research Society 1982).

The analytical tool used in this study to model walls under axial and bending loads is a finite element computer program, FINWALL, developed by Anton Polensek at Oregon State University, Corvallis, Oreg. This model accounts for both I-beam action and lateral load distribution in its calculation of wall performance. During model development, seven walls of various configurations and 15 single-stud I-beam sections were tested to verify model accuracy (Polensek 1976; Polensek and Atherton 1976).

<sup>1</sup>Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

The computer model is currently being used to generate distributions of wall strength and stiffness using actual load-deflection data for studs tested in a large cooperative testing program (Polensek and Gromala 1983). It is anticipated that the wall performance distributions generated by FINWALL will be used to update design procedures and code acceptance criteria (Polensek and Gromala 1983). These modifications will allow designers to use improved analysis techniques as an alternative to traditional individual member analysis techniques.

As previous studies (Polensek 1978) have shown that the studs have the greatest effect on wall performance, both testing and modeling in this study concentrated on accurate definition of stud load-deflection performance. To provide this information all studs received nondestructive stiffness evaluations before the wall tests. After each wall test all surviving studs were tested to failure to determine their complete load-deflection curves. Estimates of properties for sheathings and fasteners for most of the model predictions are based on average values from previous testing (Polensek 1978). This is the way in which the wall performance distributions mentioned above are being generated.

The test program described in this report examined 10 walls, all sheathed with plywood and gypsum, using one grade of studs. Six walls were tested with studs 16 inches apart and four with 24-inch spacing.

## Materials and Methods

### Material

All material was purchased from a Madison, Wis., lumberyard. The studs were nominal 2 × 4's (precut, 92-5/8 in. long) of Douglas-fir, Stud grade. Douglas-fir, commonly used for studs in the western United States, was chosen in this study both for this reason and for comparison with data collected as part of the in-grade testing program (Galligan et al. 1980). Gypsum wallboard, 1/2 inch thick in 4- by 8-foot sheets, was chosen for interior sheathing. Two exterior plywood coverings—1/2-inch CDX sheathing and 5/8-inch combination sheathing/siding (T-111) in 4- by 8-foot sheets—were used.

### Test Frame

Uniform lateral load was provided by an air bag positioned between a strongback panel and the test wall (fig. 1). The strongback panel was constructed of 2- by 6-inch framing spaced 12 inches apart, sheathed with plywood. Axial loads were applied above each stud by a series of deadweights acting on lever arms reacting on a pipe on top of the wall (fig. 2). The resulting axial load was 1,200 pounds per stud, corresponding to application of full roof and floor design load in a typical two-story house. As specified in ASTM E 72 (ASTM 1977) for testing walls under compressive loads the reaction was positioned to be slightly (about one-sixth of wall thickness) eccentric toward the inside (or gypsum side) of the wall.

Lateral load was applied by a single polyethylene air bag. The bag was 4 inches thick by 8 feet high by 18 feet long. Six-mil-thick sheet polyethylene with heat-sealed seams was used. Two standard tire valves were installed in the bag—one for air inlet and the other for pressure monitoring.

## Procedures

Modulus of elasticity (MOE) for all studs was determined prior to the wall tests using a transverse vibration (E-computer) method. Studs were randomly chosen and assembled into 10 wall frames, each consisting of 10 studs. Six walls with studs spaced 16 inches apart were 12 feet long and the other four walls with studs 24 inches apart were 18 feet long. Double top plates and a single bottom plate were used in all frames. Studs were fastened to the plates using two 16d common nails per connection. None of the lumber was specially conditioned, and it reached an average moisture content of 8 percent (range = 7-11 pct), as measured by a resistance-type moisture meter at the time of test.

For each test, a wall frame was first sheathed with plywood. Nails (6d for 1/2-in. and 8d for 5/8-in. sheathing) were spaced at 6 inches around the perimeter of each sheet and 12 inches on the interior. A layer of polyethylene sheet was taped to the plywood to protect the air bag from small tears. The wall was then nailed into a sill plate on the bottom and bolted to the strongback panel on top. For some walls, internal deflection transducers to measure stud-sheathing slip were positioned at this time. Finally, gypsum wallboard was applied (4- by 8-ft sheets) vertically with standard "drywall" nails spaced 8 inches apart. Joints were taped and spackled and allowed to cure for at least 1 day prior to each test.

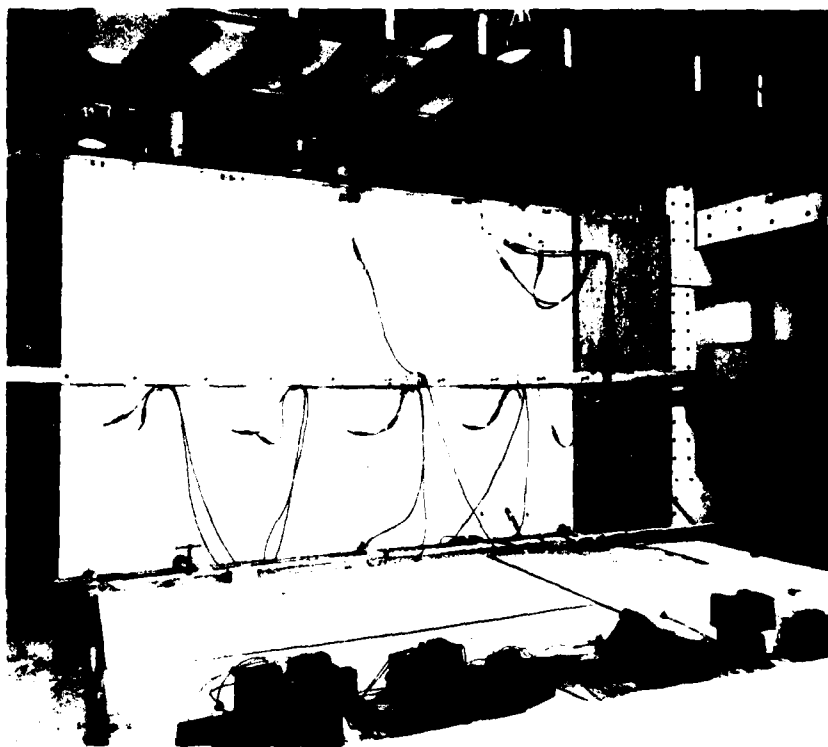


Figure 1.—Overall test setup with lever arms on top of wall, dead weights in foreground, instrumented wall in background. (M150 604)

The end studs were directly adjacent, but not attached, to infill panels. Thus the structural support conditions of the wall are "free" on the ends and "simply supported" on the top and bottom.

## Instrumentation

Linear variable differential transducers (LVDT's) were used to measure midspan deflection of each stud, plate slip, and sheathing-stud slip at selected locations. A vertical water manometer was used for measuring load. Measurements were taken by reading the water level in the manometer and manually recording it, while all deflection readings were electronically scanned and recorded on magnetic tape. Although it is difficult to assess the precision of the vertical water manometer, load readings are estimated to be within  $\pm 1$  pound per square foot (lb/ft<sup>2</sup>).

## Load Application

At the beginning of each test initial deflections were recorded, and the axial load was then applied. Deflections were recorded after application of the axial load and at approximate 10-lb/ft<sup>2</sup> intervals of lateral load. At each interval, loading was stopped for a few seconds while deflection readings were taken. As the walls began to fail, readings were recorded as frequently as the electronic equipment could record all channels (about every 14 sec). Time to failure averaged about 12 minutes, indicating an average load rate of about 10 lb/ft<sup>2</sup> per minute. For six of the walls, loading was applied in this way until a significant failure occurred, causing the load to substantially drop. It was necessary to load four of the walls more than once because of leaks in the air bag, which caused the load to drop off before any studs failed.

## Test Results

### Stud Tests

After each wall test, the studs that had not failed were tested to failure in third-point bending by ASTM D 198 procedures (ASTM 1976). Load and midspan deflection were continuously plotted for each test. In addition to these tests, 19 control specimens from the same population of studs were tested for comparison.

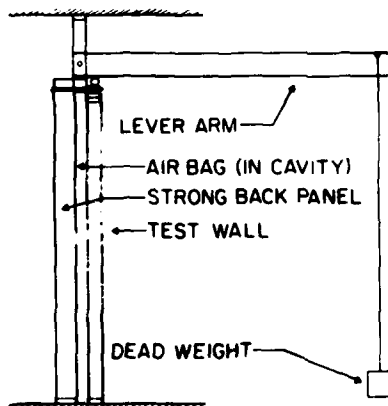


Figure 2.—Schematic of test.  
(ML83 5458)

### Walls

**Stiffness.**—It is difficult to evaluate the acceptability of the deflection of these walls because no stiffness-related design criteria exist for walls, although a span/deflection ratio of 140 to 150 at design windload has been proposed by the NAHB Research Foundation (1973). The overall average deflection of 0.28 inch at 30 lb/ft<sup>2</sup> measured in these tests corresponds to a span/deflection ratio of 330. The average at 20 lb/ft<sup>2</sup> (0.15 in.) corresponds to a span/deflection ratio of 600.

Average and maximum stud deflections are shown (table 1) for each wall at loads of 20, 30, and 40 lb/ft<sup>2</sup>. This is the range of loads that might be of interest for stiffness evaluations. Average deflections represent the average of the eight interior studs in the wall to eliminate "end effects."

As shown in a typical load-deflection curve for a stud in one of the walls (fig. 3), the eccentric placement of axial load induced negative initial deflections. Thus, any acceptance criterion that describes wall performance simply in terms of deflection at a given load level without specifying initial deflection due to the eccentric axial load is incomplete. The slopes of the wall-load versus stud-deflection curves may be better indicators of wall response. Table 1 includes deflection values for three increments of load from which slopes can be calculated.

**Strength.**—Maximum wall loads ranged from 88 to 130 lb/ft<sup>2</sup>—about 4 to 6 times a common design load of 20 lb/ft<sup>2</sup>. A load of 20 lb/ft<sup>2</sup> corresponds to the stagnation pressure of a 90-mile-per-hour wind. Table 1 includes additional information to provide insight into the behavior of each wall at failure. As noted, failure did not always occur solely in bending. In three walls the stud-plate connection was a contributing cause of wall failure (see

Appendix A). For other walls, this connection was reinforced to induce bending, rather than connection, failures. Both failure modes are shown in figure 4.

There was no consistent difference between walls sheathed with either type of plywood sheathing. The walls with studs 24 inches apart were, on the average, weaker by about 8 percent than the walls with studs 16 inches apart. When all maximum loads were grouped together, the resulting overall average was 115 lb/ft<sup>2</sup>. Even though this sample of 10 walls contained different failure modes, sheathing types, and stud spacings, the coefficient of variation was only 12 percent.

### Studs

The 84 studs that survived the wall tests had an average modulus of rupture (MOR) of 6,190 pounds per square inch (lb/in.<sup>2</sup>) with a coefficient of variation of 32 percent (table 2). The average initial MOE of this group was 1.6 million lb/in.<sup>2</sup> with a coefficient of variation of 20 percent. These values are not significantly different from the results of tests on the 19 control specimens. The average MOE of the 16 studs that broke in the wall tests was about 11 percent lower than that of the remainder of the sample. This difference is statistically significant.

Table 1.—Summary of wall tests

Wall No.	Sheathing type <sup>a</sup>	Number of times loaded	Deflection at load level <sup>1</sup> of						Strength		Comments
			20 lb/ft <sup>2</sup>		30 lb/ft <sup>2</sup>		40 lb/ft <sup>2</sup>		Maximum load	Number of broken studs	
			Average	Maximum	Average	Maximum	Average	Maximum			
16-INCH SPACING											
1	T	2	0.13	0.16	0.26	0.31	0.39	0.46	125	1	Combined failure modes
6	T	4	.30	.37	.36	.44	.50	.63	125	2	Two adjacent studs failed
7	C	4	.16	.20	.23	.30	.30	.39	114	1	One stud failed
8	T	1	.13	.16	.26	.30	.39	.44	120	2	Two adjacent studs failed
9	C	1	.10	.16	.18	.25	.28	.35	130	2	Combined failure modes
10	C	1	.09	.14	.18	.23	.27	.37	127	5	Five studs failed
24-INCH SPACING											
2	T	1	.13	.22	.29	.39	.44	.58	94	0	Plate-stud failure
3	C	1	.14	.19	.32	.40	.41	.50	114	2	Two adjacent studs failed
4	C	1	.15	.21	.26	.35	.42	.53	88	1	One stud failed
5	T	2	.21	.26	.33	.40	.45	.53	109	1	One stud failed

<sup>1</sup>All average deflections represent the average of 8 interior studs. For walls that were loaded more than once, deflections shown are those of the final test.

<sup>a</sup>T = 5/8-in. T-111, C = 1/2-in. CDX.

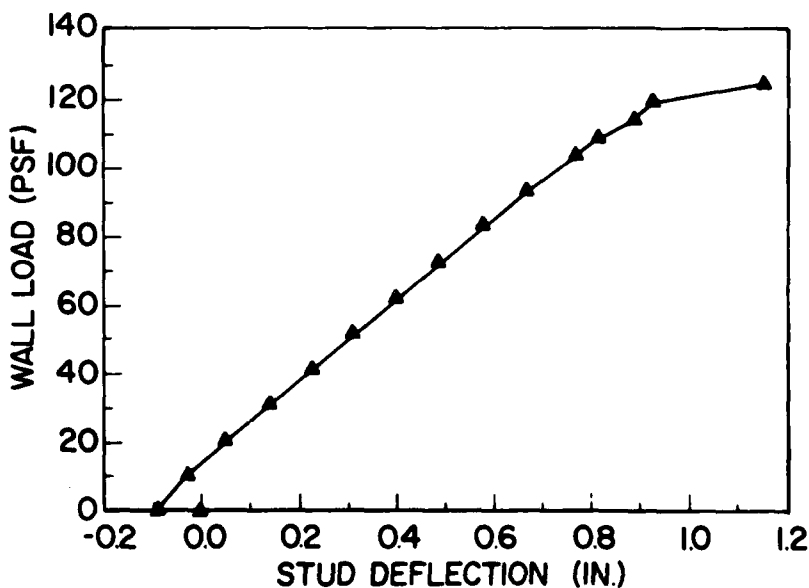


Figure 3.—Typical load-deflection curve for a stud in a wall. (Note that eccentric axial load induced negative deflection at zero lateral load.) (ML63 5459)



## Predictability of Wall Performance



Figure 4—Bending failure (left); failure of stud-plate connection (right). (M150 625-5) (M150 700-5)

As previous reports on performance of light-frame wall systems indicate (Polensek 1976), elementary analysis methods are not adequate to estimate wall strength and stiffness. Although it is difficult to quantify the conservatism of elementary methods, one can calculate failure loads of individual studs using these methods as an approximate indicator.

Analysis methods that neglect composite wall behavior (both I-beam action and lateral load distribution) assume that only the studs are stressed and that each stud takes an equal share of the imposed load. If these assumptions are true, one could calculate the stress in the studs when each wall fails. For example, the weakest wall failed at 88 lb/ft<sup>2</sup>, which would induce a stress of 5,140 lb/in.<sup>2</sup> in each stud under these assumptions. However, of the studs that survived 88 lb/ft<sup>2</sup> in this wall, bending tests showed that three of them had strengths less than 5,140 lb/in.<sup>2</sup>. Thus, although only one stud failed at 88 lb/ft<sup>2</sup>, elementary analysis methods predict three other studs would have also failed—at loads of 54, 74, and 83 lb/ft<sup>2</sup>. In 8 of the 10 walls, elementary methods predict at least 1 "false" failure in each wall, at loads substantially less than the maximum wall load. Calculations of average wall stiffness show similar conservatism.

Accounting for lateral load distribution while keeping track of the I-beam action in the wall is easily accomplished by computer. Program FINWALL (FINITE element analysis of WALLS) uses a linear step-by-step technique to predict wall strength and stiffness. Details regarding the program and its internal workings are described by Polensek (1976). Information regarding input data for the program is in Appendix B.

Table 2.—Results of stud tests

Stud group	Number of specimens	Results of ASTM D 198 tests					
		Nondestructive modulus of elasticity		Modulus of elasticity		Modulus of rupture	
		Average	Coefficient of variation	Average	Coefficient of variation	Average	Coefficient of variation
		Million lb/in. <sup>2</sup>	Pct	Million lb/in. <sup>2</sup>	Pct	Lb/in. <sup>2</sup>	Pct
From wall tests							
Failed in wall	16	1.42	14	—	—	—	—
Not failed in wall	84	1.63	16	1.60	20	6,190	32
Control specimens	19	1.60	17	1.53	17	5,910	40
Combined	119	1.60	17	—	—	—	—

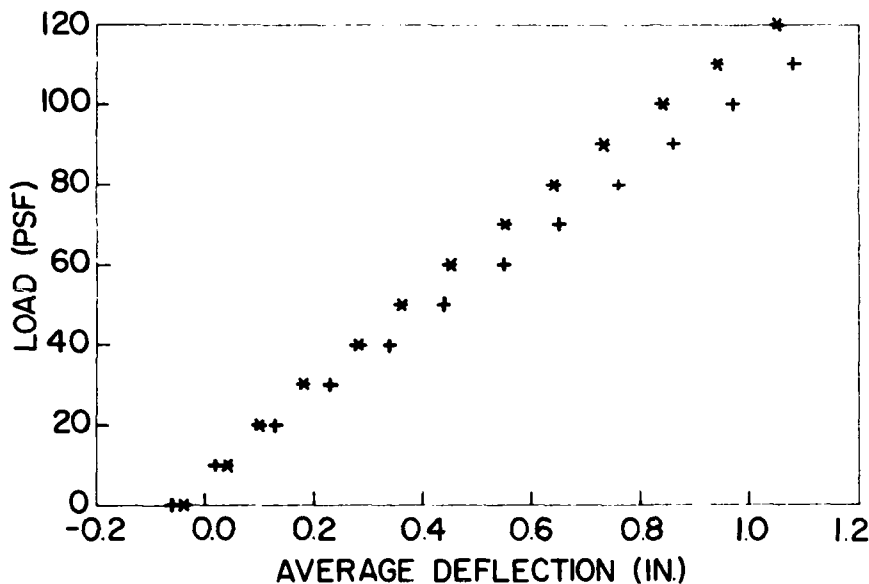


Figure 5.—Wall load versus average wall deflection.  
 \* = test data, + = model prediction.  
 (Note that eccentric load induces negative deflection at zero lateral load.) (ML83 5460)

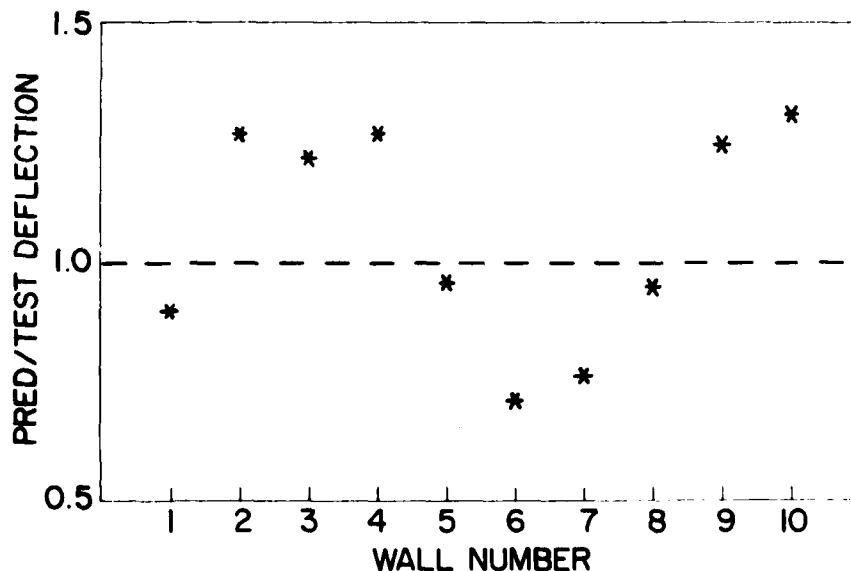


Figure 6.—Deflection predictions for all 10 walls. (Based on ratios for eight interior studs in each wall.) (ML83 5461)

## Stiffness

Initial attempts to correlate test versus predicted deflections for the walls were confusing. Although plots of load versus deflection (fig. 5) showed good agreement, summaries of predictability showed widely varying accuracy (fig. 6). Closer examination of the data revealed two potential sources of variability: First, the test walls had unusual variations in the amount of negative deflection induced by the eccentric axial load at the beginning of the test; and second, predictability of walls loaded once to failure was worse than for walls loaded more than once. As explained more fully in Appendix C, a series of supplemental analyses was conducted to address both of these issues. The results of these analyses show marked improvements in predicting deflections when specific details of each test are considered.

Figure 6 is based on the average ratio of predicted deflection divided by measured deflection (in the load range of 20-40 lb/ft<sup>2</sup>) for the eight interior studs in each wall. The overall average for all walls was 1.06 (range = 0.71-1.31). Examination of the relationship between load level and predictability showed little correlation, indicating that predictability was independent of load level.

## Strength

As discussed in previous reports, predictability of wall strength is based on proper definition of the complete load-deflection relation for all the studs in the wall. For studs that broke during a wall test, Polensek and Atherton (1976) used a previously determined estimate of initial MOE and assumed linear behavior to failure. They assumed that failure deflection in the wall test determined the stud's individual failure deflection. The same procedure was used in this study.

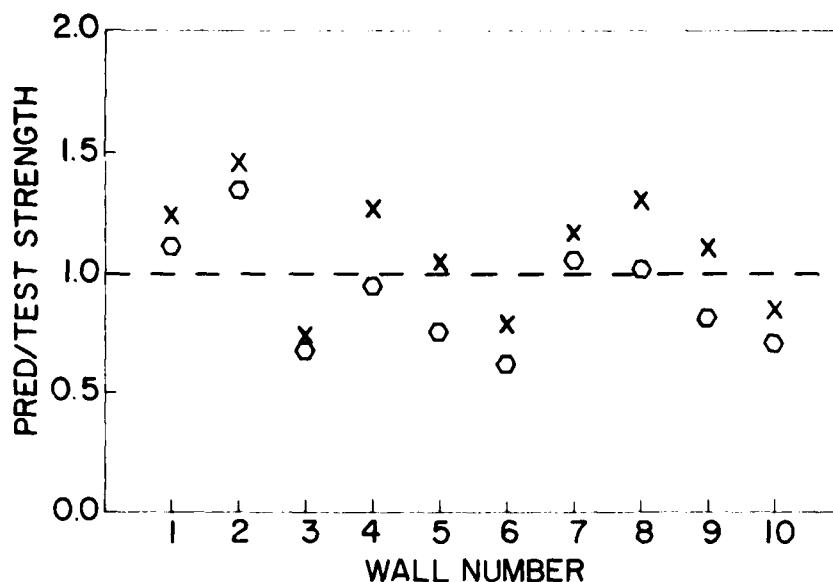


Figure 7.—Strength predictability for all 10 walls.  
 O based on model-predicted first stud failure.  
 X based on model-predicted maximum load.  
 (ML83 5462)

It should be noted that predicted wall failure load is highly sensitive to choice of stud failure deflection. In two of the test walls (Nos. 3 and 6), adjacent studs failed in rapid succession. In these tests, it was difficult to determine stud failure from the deflection measurements in the wall due to multiple "jumps" in the measurements. For these walls, slight changes in the choice of stud failure deflection caused large changes in predicted failure load.

Figure 7 shows predicted/test ratios for maximum wall load. Two points are shown for each test: The lower point corresponds to FINWALL's prediction of first stud failure, and the upper point is the prediction of two adjacent stud failures. Due to the rapid succession of failures in some of the tests and the difficulty in defining failure of a single stud within the wall, only one test load (maximum load) is given. As discussed

previously, and described further in Appendix A, the tests were usually terminated when a stud failure caused the load to drop off significantly. No attempt was made to measure wall behavior beyond this point. It is believed that some of the walls, especially those in which fewer than two studs broke, still had reserve capacity when the tests were terminated.

The average predicted/test ratio was 1.10 (range = 0.79 -1.46) using predicted maximum wall load as a basis and 0.91 (range = 0.62 -1.35) using predicted first stud failure as a basis.

## Effect of Stud Spacing

Computer simulations in a previous study by Gromala and Polensek (1982) predicted that walls with studs 24 inches apart would be about 60 to 70 percent as stiff and strong as walls with studs 16 inches apart. In this test series, the ratio was about 82 percent. The computer model predicted that for these groups of studs the walls with studs 24 inches apart would average 84 percent as strong as the walls with 16-inch spacing.

Closer examination of the stud data shows that the properties of the surviving studs were slightly higher for the walls with 24-inch stud spacing. This difference, 8 percent for strength and 6 percent for stiffness, was not statistically significant.

Although the difference in performance in this small sample (ratio = 0.82) was not as great as would generally be expected, the model predictions are consistent with the results. Because of the limited number of tests, the confidence interval on the 0.82 ratio is wide (about  $\pm 15$  pct). Thus, the data do not contradict the hypothesis that two walls constructed with identical studs with spacings of 24 and 16 inches, respectively, would have a ratio of strengths and stiffnesses of approximately two-thirds.

## Discussion of Predictability of Experimental Behavior

In order to display the predictability of program FINWALL objectively, the summary figures 6 and 7 were based on identical presentations of data for all 10 walls. For walls tested more than once, the deflections in the final test were used as the basis for figure 6. For walls that "failed," due in part to stud-plate connection failures or to deficiencies in the air bag, the wall's capacity was reported as the highest load achieved during the test, whether "capacity" was achieved or not. Such reporting obscures the ability of FINWALL to predict the performance of "ideal" walls that would fail only in bending and always on the first test attempt.

A clearer picture of true predictability is obtained if one looks more closely at the specific details of each test. For example, FINWALL significantly overpredicts deflections of Walls 2, 3, 4, 9, and 10 as displayed in figure 6. However, as shown in table 1, these are five of the six walls loaded only once. Supplemental testing (Appendix C) showed that the initial nail slip modulus for the material used in this study was substantially higher than that cited by Polensek (1978) and used for these predictions. Thus, the walls loaded once to failure should be modeled with the higher slip modulus. On the other hand, as the main effect of repeated loading on joints is to decrease the initial slip modulus, it is not surprising that the lower slip values (from Polensek (1978)) accurately predict deflections in the four walls loaded more than once.

Closer examination of figure 7 reveals similar trends in predictions of wall strength. Walls 1 and 2, predicted by FINWALL to be stronger than the tests showed, did not get a chance to reach their bending capacity in the tests. Walls 3 and 6 are somewhat underpredicted; these two walls, as discussed previously, had adjacent stud failures in the tests. As failure deflection of each stud individually was difficult to assess, conservative estimates were used, resulting in low predictions.

The major point of this discussion is that "reasonable" refinement of the input data for FINWALL (reflecting how the test **actually** behaved rather than how it **should** have behaved) consistently pushed the model prediction closer to observed behavior. In the main body of this paper, however, the predictions are not reported in this manner to eliminate the possibility for introducing "fudge factors" into the analysis.

This discussion is pertinent in that it reflects that FINWALL is capable of producing better predictions as model inputs are refined. Based on such refinements (Appendix C), the model would be able to predict the stiffness of each test wall within about 10 percent. These analyses show that prediction of wall failure load is inherently less precise than prediction of deflections. Part of the problem is apparently in the idealization of the load-deflection relations for studs that fail in the wall.

## Summary and Conclusions

Light-frame wall systems constructed of Douglas-fir studs (Stud grade) sheathed with plywood and gypsum greatly exceed structural design requirements. Testing large assemblies such as 12- to 18-foot-long walls is costly, and such tests are difficult to conduct.

A finite element computer model, FINWALL, has been shown to be accurate in its prediction of wall stiffness for a conventional wall configuration. The best accuracy has been obtained when experimentally determined slip values replaced values from previous testing in the literature. Prediction of wall strength is reasonably accurate. These predictions are sensitive to the material properties used as input, especially the failure deflections of the studs.

Based on deflections in the final test on each wall, FINWALL predicts average deflection to be 6 percent higher than test values. Predictions ranged from 71 to 131 percent of test values. However, in every case in which a problem with a test could have influenced measured stiffness, elimination of the problem should have modified the test value closer to predicted.

Results for strength were similar but not as accurate. Maximum wall loads are reported and compared with model predictions regardless of wall failure mode. Even though the model can only predict bending failures, predictions for 10 walls were good, averaging 10 percent higher and ranging from 0.79 to 1.46 times test values. As nearly half of the tests were terminated after only one stud failed, it is not surprising that the model's prediction of first stud failure, when compared to maximum test load, is a slightly better predictor, averaging 9 percent below test values.

Based on these tests and numerous computer runs conducted to predict their results, the author concludes that FINWALL is a useful analytical tool. Although overall ranges of predictability were somewhat large, they were based on grouping all test results regardless of failure mode and analyzing them all the same way. By carefully studying the idiosyncrasies of each test and modifying inputs accordingly, the author was able to predict performance of these walls within the 10 to 20 percent accuracy range.

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## Appendix A—Discussion of Test Details

The author believes that additional discussion of specific details regarding the tests will convey a better understanding of the behavior of these walls under load. This Appendix is intended to provide this information.

### Equipment

**Air bag.**—The single biggest problem encountered in this test program was leaks in the air bag. Four of the walls had to be taken out of the frame and reinserted after the bag was repaired. Multiple testing and excessive handling may have weakened these walls. In addition, anticipation of further damaging the air bag may have influenced premature decisions to terminate some of the tests after the failure of only one stud.

**Manometer.**—Measurement of air pressure using a vertical water column is an accurate and time-tested technique. In these tests, however, when the air inlet was manually controlled and the deflection readings were triggered electronically by pushing a record button, precise correlation of corresponding load levels and deflection readings was exceedingly difficult. This was especially true near failure when readings were taken 15 to 20 seconds apart.

### Loading and Construction

**Eccentric load.**—The application of axial load at a slight eccentricity corresponded to both ASTM E 72 and to Polensek's previous tests. In these tests a pipe support was used only on the top of the wall, whereas Polensek used such a support both top and bottom. It was felt that using a pipe support at the bottom in these tests would complicate the fastening of the wall bottom and create a potential safety hazard.

Analysis of data after the tests showed that the negative stud deflections induced by the eccentric load were sometimes not overcome until 20 to 30 lb/ft<sup>2</sup> of lateral load was applied. This "reinforcing" effect is not realistic when one considers that large axial loads may not be present in an actual structure when design-level lateral load is present. In addition, the true eccentricity in axial load in a real structure would be influenced by factors such as wind direction (windward wall or leeward wall), upper floor and roof stiffness, and squareness of the stud ends. For these reasons, the author recommends that future wall testing not include an eccentric load that reinforces the wall.

**"Leeward" loading.**—Walls 5 and 6 were initially loaded on the gypsum side of the wall, simulating the outward force (suction) on a leeward wall under windload. For a leeward wall the axial load, if placed eccentrically toward the gypsum side, acts in the same sense as the lateral load. Thus, deflections at 20 to 40 lb/ft<sup>2</sup> for these walls were more than double the deflections for the same walls with reverse eccentricity. Actual stiffness values (slope of the load-deflection curve) were about equal for both load cases.

In both walls the gypsum failed before any of the studs. Wall 5, with studs 24 inches apart, was loaded to 75 lb/ft<sup>2</sup> and Wall 6, with studs 16 inches apart, reached 105 lb/ft<sup>2</sup>. At these loads, progressive cracking of the gypsum prevented loading to higher levels. Both walls were subsequently taken out of the test frame, sheathed with new gypsum wallboard, and tested as windward walls (loaded on the plywood side).

Although limited in scope and exploratory in nature, the tests showed that the eccentric placement of axial load results in significantly different deflection measurements for walls loaded on the interior sheathing side. The results also indicate that walls laterally loaded on 1/2-inch gypsum wallboard will exhibit failures in the gypsum. Based on results of two tests, these failures would be expected to occur about 20 to 30 lb/ft<sup>2</sup> before stud failures, but still substantially higher than design loads.

**Stud-plate connection.**—In the first wall tested, the studs began to split out at the sole plate connection at about the same load that a stud failed (called "combined modes" in table 1). In the second wall, the plate split before any studs failed. Steel reinforcing angles were placed on the next six walls to prevent such splitting. These angles were inadvertently left off Wall 9, and two studs failed in bending at approximately the same time that two studs split at the sole plate.

It is difficult to judge whether the walls that failed in "combined modes" would have been significantly stronger had the stud-plate connection been reinforced. Based on the performance of the other walls and on subjective observations of these walls during the tests, the author believes that the bending capacities of these walls would have been only slightly higher than the reported failure loads.

Although failure of the stud-plate connection may actually govern wall strength in some cases, the author does not recommend that it be rigorously modeled. If walls are someday engineered so that design loads are nearer to wall failure loads, the problem will warrant additional study—probably in the form of improving the connection rather than modeling it to predict its behavior.

## Appendix B—Inputs Used For FINWALL

**Loading** Axial compressive = 1,200 lb.  
Moment (eccentric) = -900 in.-lb.

**Studs** Multilinear as measured in bending tests. Linear, for studs that failed in wall, with initial MOE previously determined and failure deflection as in wall.

**Sheathing** Gypsum:  $E_x = 0.358 \times 10^6 \text{ lb/in.}^2$ ,  $E_y = 0.232 \times 10^6 \text{ lb/in.}^2$ ,  
 $G = 0.159 \times 10^6 \text{ lb/in.}^2$ ,  $(E_x)_{\text{axial}} = 0.163 \times 10^6 \text{ lb/in.}^2$ ,  
 $(E_y)_{\text{axial}} = 0.093 \times 10^6 \text{ lb/in.}^2$ ,  $t = 0.5 \text{ in.}$   
Plywood: (T-111)  $E_x = 1.4 \times 10^6 \text{ lb/in.}^2$ ,  $E_y = 0.300 \times 10^6 \text{ lb/in.}^2$ ,  
 $G = 0.156 \times 10^6 \text{ lb/in.}^2$ ,  $t = 0.625 \text{ in.}$ , (CDX) same elastic  
properties,  $t = 0.5 \text{ in.}$

Fasteners	Slip modulus	to	Slip level
Plywood	4,100 lb/in.		0.025 in.
	2,000 lb/in.		.075 in.
	900 lb/in.		.120 in.
Gypsum	14,000 lb/in.		.0015 in.
	1,600 lb/in.		.030 in.
	300 lb/in.		.120 in.

## Appendix C—Supplemental Analyses

During initial technical review of this report, it was suggested that model predictability might be improved if samples of the studs, sheathing, and fasteners from this study were tested to determine nail slip and sheathing properties. This appendix provides limited data on slip moduli and plywood modulus of elasticity and discusses the results of supplemental computer runs using these data.

Although the main objective of this study was to concentrate on definition of stud properties to predict wall performance, a small number of fastener and sheathing tests were performed. The 30 lateral nail resistance tests showed a significantly higher average initial stiffness (fig. C1) than Polensek's (1978) tests for the plywood-stud joints. Moduli for gypsum-stud joints were similar to those in the same reference. In addition, center point bending tests on 33 small plywood specimens showed slightly lower  $E_x$  values than Polensek's (1.1 vs. 1.4 million lb/in.<sup>2</sup>).

All 10 walls were reanalyzed using these nail slip and plywood  $E_x$  values. For the walls that were tested only once these input properties provided significantly better predictions of strength and stiffness, with the exception of Wall 8.

For the walls that were loaded more than once, the nail slip and plywood values from Polensek (1978) provided better predictions. This is as expected since the slip moduli after the first loading would be expected to be lower than the initial modulus. Thus the lower values (Polensek 1978) should better represent the true moduli on reloading.

In addition to introducing new slip moduli and plywood  $E_x$  values in these supplemental analyses, one other variable was examined. As mentioned in Appendix A, the effect of leeward wall windloads was briefly examined, starting with Wall 5. Walls 5 and 6 were both loaded initially on the gypsum side of the wall.

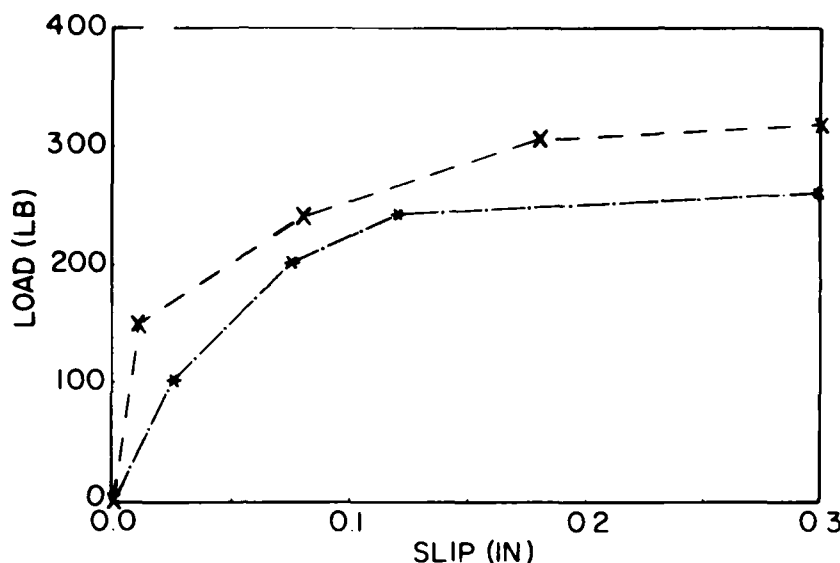


Figure C1.—Average load-slip curves for plywood-stud joints.

\* = based on data from Polensek (1978).

X = based on tests from this study. (ML83 5463)

The deflection readings on the initial tests of these walls show that the eccentricity of the axial load was positive (acting in the same sense as the lateral load). However, the data indicate that the eccentricity in the final tests on Walls 6 and 7 was not consistent. The model predictions that best fit the data indicate that it is probable that the eccentricity in the final test on Wall 5 was properly reversed to a windward wall (negative eccentricity) condition, but Walls 6 and 7 were apparently loaded with zero eccentricity. Thus, either during application of the axial load dead weights or during repositioning of these walls (they were loaded four times each), the upper pipe reaction was apparently moved about three-fourths of an inch out of position.

Figures C2 and C3 are based on slip and plywood values from Polensek (1978) for Walls 1, 5, 6, and 7 (loaded more than once) and on limited test data from this study for the remaining walls. The ratios shown for Walls 6 and 7 are based on the zero eccentricity prediction. The results shown in figures C2 and C3 can be summarized as follows:

Deflection:

Average prediction = 0.94  
(range = 0.72-1.02)

Strength (first stud basis):

Average prediction = 1.04  
(range = 0.57-1.77)

Strength (max. load basis):

Average prediction = 1.28  
(range = 0.73-1.90)



As the figures show both deflection and strength predictions for Walls 3, 5, 7, and 10 are excellent. All of these walls failed normally (stud bending). Walls 1, 2, and 9, which all failed due to combined plate failures and stud bending, are all predicted to be stronger than their test maximum loads.

Wall 4, which also failed in bending, is predicted to be substantially stronger than its unexpectedly low failure load of 88 lb/ft<sup>2</sup>, and Wall 6 is predicted to be appreciably weaker than its 125 lb/ft<sup>2</sup> failure load. For both of these walls, predictability of failure loads is apparently limited by the inability to define the load-deflection curve for the failed studs.

The model predictions for Wall 8 were unexpectedly better (deflection ratio = 0.95, load ratios = 1.01-1.31) when the lower slip values from Polensek (1978) were used (figs. 6 and 7 in text). The test deflection profile for this test was skewed toward one edge at higher load levels (fig. C4), indicating possible "bunching" or "wraparound" of the air bag resulting in nonuniform loading. Prior to this test a new system of air bag end restraint had been installed to replace the previously used infill panels. The combination of skewed deflection profile and failure of stud Nos. 1 and 2 in this test strongly suggest that the left end bag restraint was not properly anchored during this test.

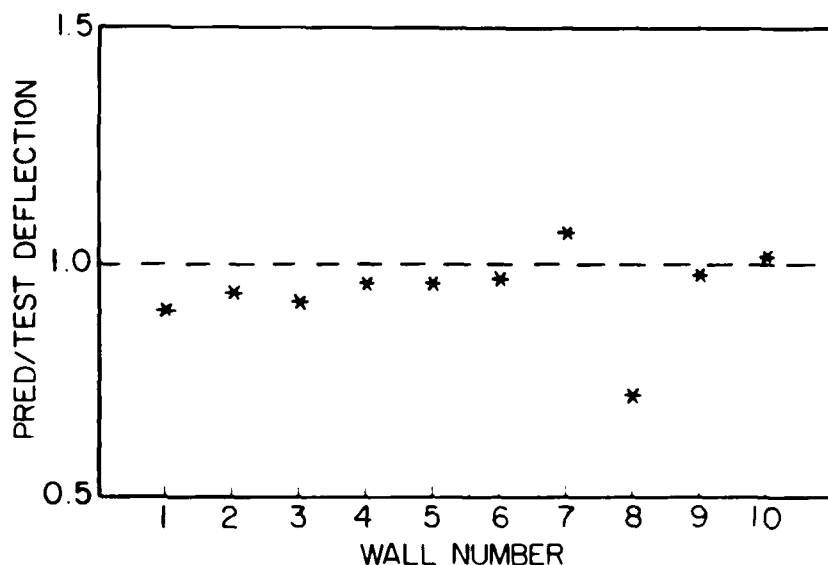


Figure C2.—Deflection predictions for all 10 walls from supplemental analyses. (Based on ratios for eight interior studs in each wall.) (ML83 5464)

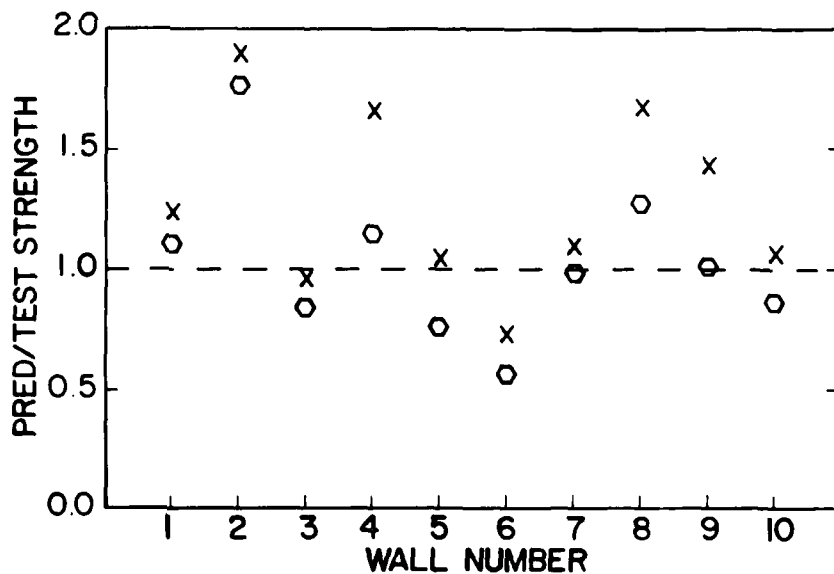


Figure C3.—Strength predictions for all 10 walls from supplemental analyses.  
 O = based on model-predicted first stud failure.  
 X = based on model-predicted maximum load.  
 (ML83 5465)

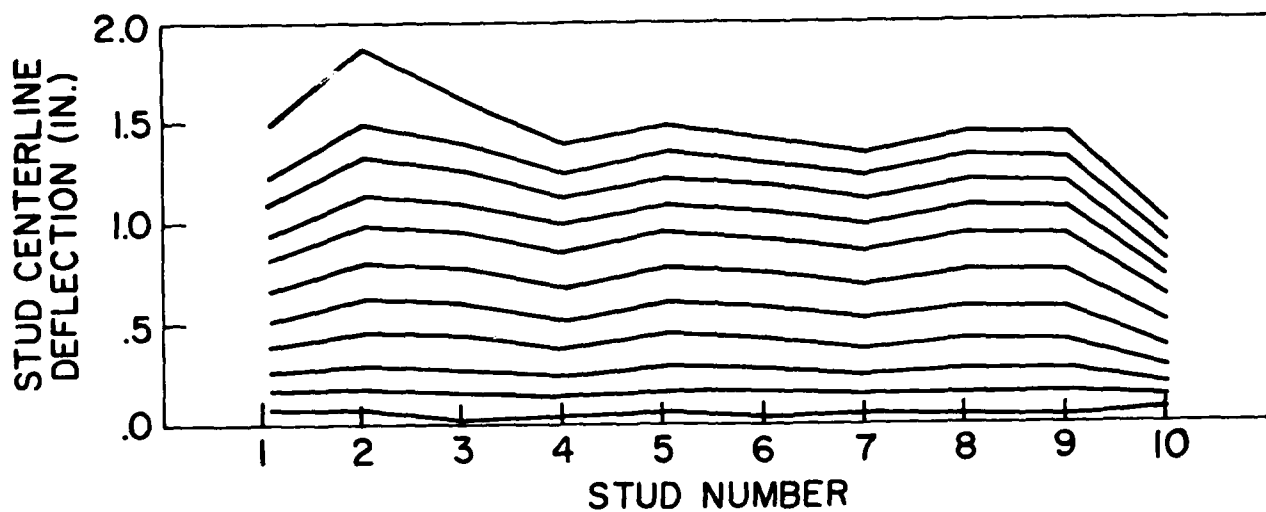


Figure C4.—Deflection profile for Wall 8, skewed to left, indicating possible "wraparound" of air bag. (ML83 5466)

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Gromala, David S. Light-frame wall systems: performance and predictability.  
USDA For. Serv. Res. Pap. FPL 442. Madison, WI: Forest Products  
Laboratory; 1983. 14 p.

This paper compares results of wall tests with analytical predictions of performance. Conventional wood-stud walls of one configuration failed at bending loads that were 4 to 6 times design load. The computer model overpredicted wall strength by an average of 10 percent and deflection by an average of 6 percent.

Keywords: Wood-stud, walls, light-frame, house, structure, test, analysis.

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